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Solar Photo Voltaic Water Pumping: Harnessing Maximum Power

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Abstract- **Among alternate sources of electricity, Solar Photo Voltaic (PV) energy is gaining prominence due to its plentiful availability. Water pumping is an important application of solar PV power. However people are not opting for it in large numbers as the 'cost per watt' for solar pumping systems is high. The cost can be reduced by harnessing more power per unit installed capacity of the solar panel. One method of realising this is by Maximum Power Point Tracking (MPPT) wherein a power electronic converter is used to match pump with the PV panel. Widely employed approach for MPPT is to monitor the PV panel power and keep on adjusting the duty cycle of converter so that tapped power is always maximum. Present paper proposes a novel method to realise MPPT for standalone solar PV water pumping system. It is shown that the output power becomes the maximum when the motor voltage becomes the maximum. Conversely, varying the duty cycle of the converter such that load voltage is always maximum leads to harnessing maximum power output. This approach can be referred to as Maximum Load Voltage Point Tracking (MVPT). We need to monitor only load voltage. It is simpler than monitoring PV panel power as in that case it's necessary to measure both panel voltage and current and then find their product.**

The proposal of MVPT for realizing MPPT is substantiated by theoretical explanation considering two types of loads: Pure Resistance and Centrifugal Pump driven by Permanent Magnet (PM) brushed DC Motor. The Matlab-Simulink based simulation is also carried out. Simulation results are found to be in close conformity with the theoretical findings.

Index Terms: **Maximum Power Harnessing; Water Pumping; Solar Photo Voltaic; Brushed DC Motor Pump.**

I. Introduction

People are not opting for solar PV based Water pumping in big nunber as the "cost per watt" of these systems is high. Around the world only 60000 solar pumping systems are installed [1]. This number is just 5000 in India [2]. The cost can be reduced by harnessing more power per unit installed capacity of the solar panel.

Solar PV panel exhibits [3] typical "Voltage vs. Current" (V_p-I_p) (Fig.1) and "Voltage vs. Power" (V_p-P_p) (Fig.2) characteristics as a function of solar radiation. At each radiation, represented proportionally by the panel short circuit current I_{ph}, there exists a particular operating point at which the output power of the panel becomes the maximum. The process of controlling the operating point of solar PV panel so that it always corresponds to maximum power at the corresponding radiation is referred to as Maximum Power Point Tracking (MPPT). This needs matching between the load and PV panel and can be accomplished by connecting a power electronic converter with variable switching duty cycle (D) as the interphase between the PV panel and the load [4]. There exist different strategies to vary D [5] which can be broadly categorized as:

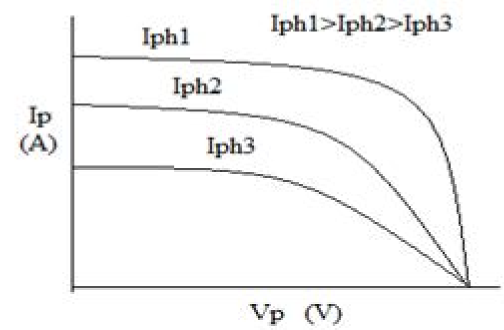

Fig.1. Typical "Vp vs. Ip" for PV Panel

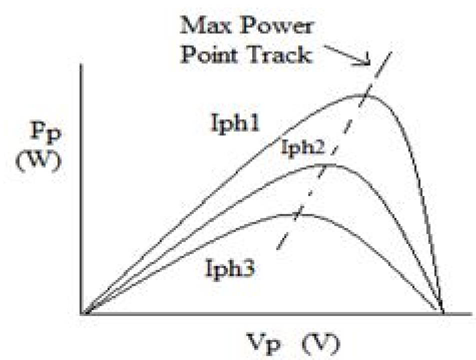

Fig.2. Typical 'V_p vs. P_p' for PV Panel

A. Interruptive Type

This has mainly two approaches. The first one is to maintain V_p at a value which is a fixed percentage of open circuit voltage (V_{oc}). This requires monitoring of V_{oc}. Another approach is to maintain the panel current (I_p) as a fixed percentage of short circuit current (I_{sc}). This requires monitoring of I_{sc}. These two approaches, though simple, require regular delinking (interruption) of panel from the load

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for measuring V_{sc} or I_{sc}, leading to loss of power harnessed.

B. Non Interruptive Type

Here the PV panel power (P_p) is monitored continuously. D is varied till P_p becomes maximum. This method is more accurate and does not require delinking of panel from load. Hence is widely employed. But for computing power ($P_p = V_p$ x I_p), two parameters (V_p & I_p) are to be measured and then multiplication operation is to be performed. This makes the controller comparatively complicated. **Hence there is a need for a method which is non interruptive as well as simple.**

Present paper proposes a simple method to realise MPPT for standalone solar PV water pumping system without battery backup. It is shown that the output power becomes maximum when the motor voltage becomes maximum. Conversely, varying the duty cycle of the converter such that load voltage is always maximum leads to harnessing maximum power output. This approach can be referred to as Maximum Load Voltage Point Tracking (MVPT). We need to monitor only load voltage which is simpler than monitoring PV panel power.

The proposal of MVPT for realizing MPPT is substantiated by theoretical explanation considering two types of loads: Pure resistance and Centrifugal pump driven by Permanent Magnet (PM) DC motor. The Matlab-Simulink (version 7.5) based simulation is also carried out. Simulation results are found to be in close conformity with the theoretical findings.

Section II of the paper brings out the proposed approach considering a simple case of pure resistive load. Section III narrates the proposed approach considering PMDC motor driven centrifugal pump load. Section IV deals with the simulation of solar water pumping system. Section V presents critical observations and discussion followed by conclusion.

II. System With Pure Resistive Load

Here the system with solar PV panel, load resistance R and a converter for MPPT (Fig.3) is considered. The converter configuration is taken as "buck-boost" due to its versatility i.e. possibility of both step down & step up operations. It acts like a transformer with transformation ratio y = D/(1-D) where D is the switching duty cycle of the converter. Let R', V_a' & I_a' be the values of R, V_a & I_a respectively referred to panel side (Fig.4).

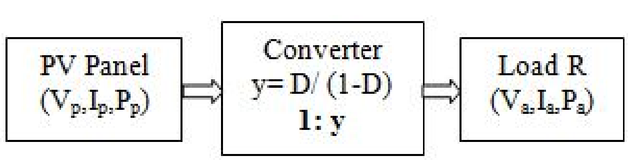

Fig.3. System with MPPT and R load

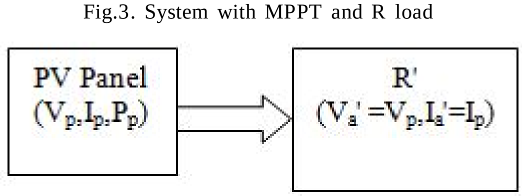

Fig.4. R load referred to panel side

For this system the following equations can be written:

$$y = \frac{D}{(1-D)} \tag{1}$$

$$R' = \frac{R}{y^2} \tag{2}$$

$$P_p = V_p I_p \tag{3}$$

$$P_a = V_a I_a \tag{4}$$

$$V_a = y V_a' = y V_p \tag{5}$$

$$I_a = \frac{I_a'}{y} = \frac{I_p}{y} \tag{6}$$

$$R' = \frac{V_a'}{I_a'} = \frac{V_p}{I_p} \tag{7}$$

Assuming 100% efficiency for converter,

$$V_p I_p = P_p = V_a I_a = P_a \tag{8}$$

$$V_a = \sqrt{P_a}\sqrt{R} = \sqrt{P_p}\sqrt{R} \tag{9}$$

$$V_a \propto \sqrt{P_a} \propto \sqrt{P_p} \tag{10}$$

Hence theoretically, equation (10) indicates that V_a follows variations of P_p. As per the typical V_p-P_p characteristics (Fig. 2), P_p rises from zero, reaches maximum and decreases to zero. So does V_a. Thus V_a becomes maximum when P_p becomes maximum.

To establish validity of (10), an actual solar panel is taken with the specifications: $P_m = 148W_p$, $V_m = 16.4$ V, $I_m = 9$ A, Sun Technics Make. It is tested and V_p-I_p characteristics are obtained at a radiation corresponding to $I_{sc} = 5.8$ A (Fig.5). The load is considered as pure resistance of value R = 2 &!. Using (2), R' is calculated for different values of D. By superimposing R' lines on the V_p-I_p plot of Fig.5, different operating points (V_p, I_p) are obtained. With these, P_p, V_a & I_a are obtained using (3), (4), (5) & (6) and tabulated (Table 1). It is observed from Table 1, that, with change in D, as panel power P_p increases (decreases), load voltage V_a also accordingly increases (decreases). Va becomes maximum when P_p becomes maximum. This is in accordance with (10). P_p and P_a values are equal due to the assumption that converter efficiency is 100% (8).

III. System with Motor-Pump Load

Here the system with solar PV panel, converter for MPPT and motor-pump load (Fig. 6) is considered. PV panel and MPPT converter are the same as mentioned in section II.

Motor-Pump Unit: It is a monoblock of PMDC motor (brushed) and centrifugal pump with the specifications: 12V,

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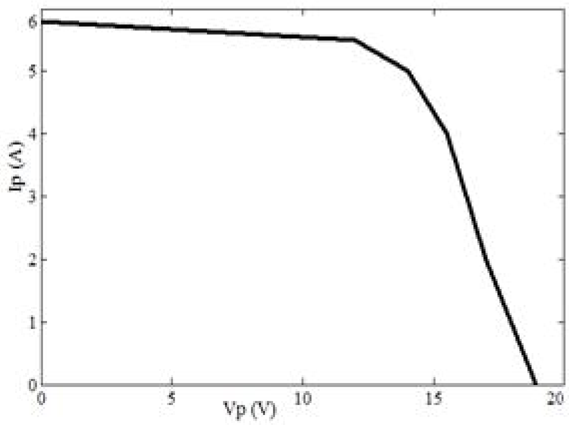

Fig.5. "V_p vs. I_p"(Exp) of PV panel

TABLE I. VALUES DERIVED FROM PRACTICAL V_p-I_p CHS FOR SYSTEM WITH MPPT & R LOAD AT I_{sc}=5.8A

D	0.30	0.35	0.40	0.45	0.50	0.55
Y	0.42	0.53	0.66	0.81	1.0	1.22
R' (Ω)	11.3	7.1	4.5	3.0	2.0	1.34
V_p (V)	17.5	16.8	16.0	14.6	10.3	6.5
I_p (A)	1.5	2.3	3.5	4.4	5.1	5.2
P_p (W)	27.1	38.6	56	**64.2**	52.5	33.8
V_a (V)	7.35	8.9	10.5	**11.8**	10.3	7.9
I_a (A)	3.6	4.3	5.3	5.4	5.1	4.26
P_a (W)	26.4	38.2	55.6	63.7	52.5	33.6

70-100W, Total Head: 9 m, Tata BP Solar make. For this unit, the following parameters are determined experimentally: Motor Inertia: 6.83 x 10-3 Kgm^2, Armature Resistance: 0.7 &!, Armature Inductance: 0.12 x 10^{-3} H, Voltage constant, K_b = 0.033 V/rad/s (Fig.7).

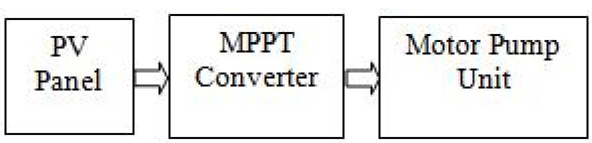

Fig.6. Solar Pumping with MPPT converter

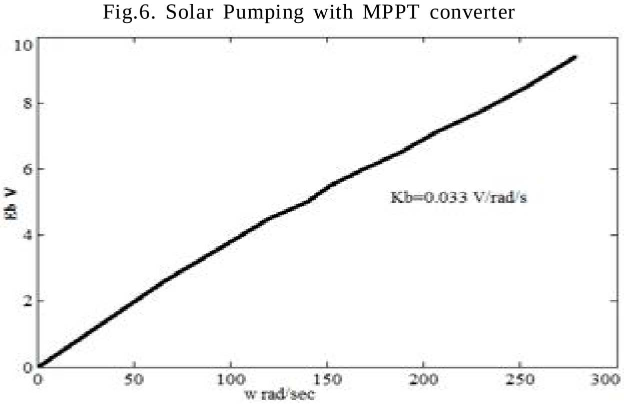

Fig.7. "ω vs. E_b" for PMDC motor

Load Equation: The pump is used to lift water with delivery head H_d = 5m. The "Speed (ω) vs. Torque (T)" characteristic is obtained experimentally to derive the pump load equation (11) which is found to be of the same format mentioned in the literature [6].

$$T = 4.8\times10^{-6}\ \omega^2 + 0.00019\ \omega + 0.092 \quad (11)$$

For PMDC motor, following equations can be written:

$$E_b = K_b\omega \quad (12)$$

$$E_b = V_a - I_a R_a \quad (13)$$

$$T = K_b I_a \quad (14)$$

Using (12) to (14), the load equation (11) can be written in terms of V_a & I_a as shown in (15).

$$4.4\,V_a^2 - 5.75\,V_a - 6.17\,V_a I_a + 2.15\,I_a^2 - 36.9\,I_a + 92 = 0 \quad (15)$$

The pump load can be represented referred to panel side (Fig.8 & 9). The referred load equation (16) is obtained using (5) and (6) in (15).

$$4.4y^2V_a'^2 - 5.75yV_a' - 6.17V_a'I_a' + 2.15\frac{I_a'^2}{y^2} - 36.9\frac{I_a'}{y} + 92 = 0 \quad (16)$$

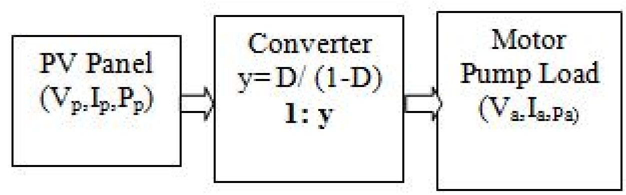

Fig.8. System with MPPT and pump load

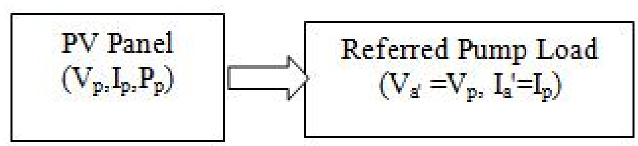

Fig.9. Motor pump load referred to panel side

V_a'-I_a' characteristics are obtained for different switching duty cycles (D) and then are superimposed with V_p-I_p characteristics of 148W_p panel at different radiations (Fig.10). The intersection points (operating points) are determined. Using these values, " D vs. V_a " (Fig.11) and " D vs. P_p " (Fig.12) characteristics are plotted. It's observed that at each radiation, power output of the panel is maximum when V_a becomes maximum. V_a shows typical increase/decrease trend with the corresponding variations in P_p. V_a corresponding to maximum power is an unique point. Thus the theoretical inference, V_a following variations of P_p, made for pure resistance load in section II, is valid for pump load also.

IV. SIMULATION OF THE SYSTEM

This section deals with the simulation of Solar PV water pumping system considering both the cases: with and without the provision of MPPT (Fig.6&13 respectively). Details of

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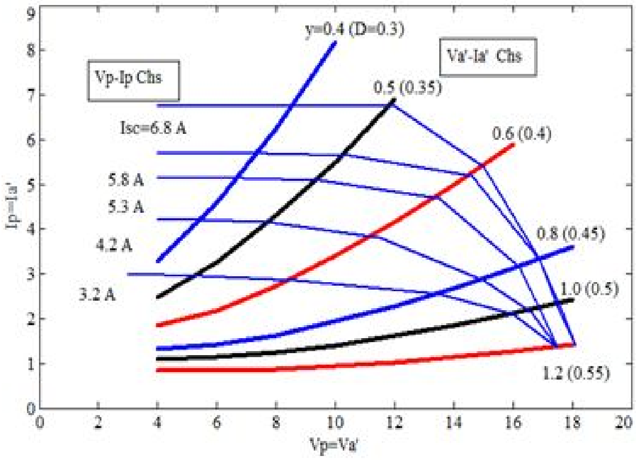

Fig.10. Panel and Motor-Pump load characteristics superimposed

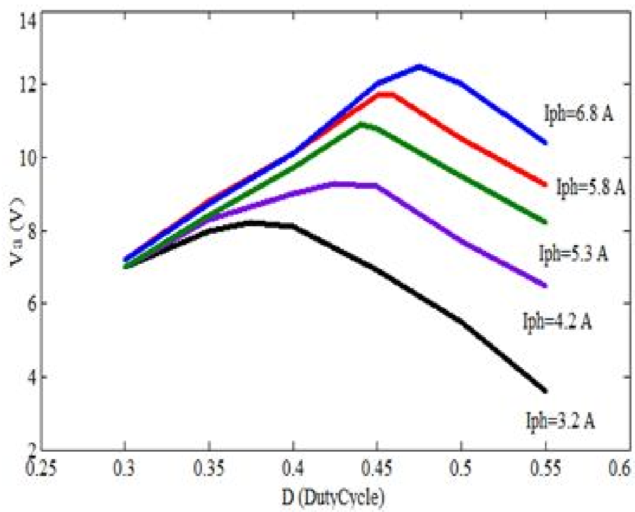

Fig.11. "Load Voltage V_a vs. D (Duty Cycle)" for motor pump load

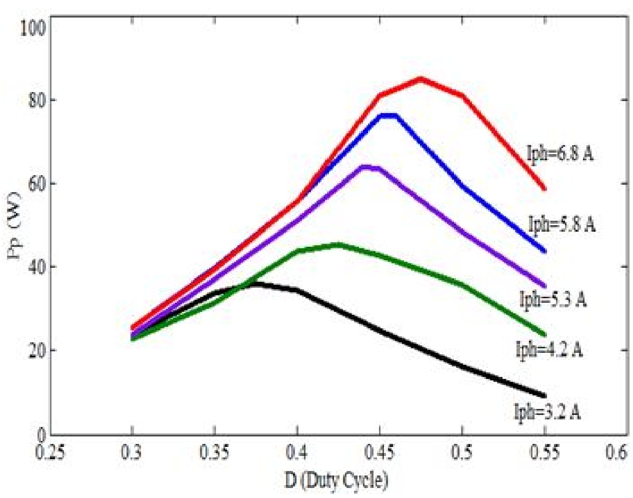

Fig.12. "Panel Power P_p vs. D (Duty Cycle)" for pump load

different components considered for simulation are given below.

PV Panel: Specifications are the same as given in section II. PV panel can be represented by a simple equivalent circuit [7] with a current source having a diode in parallel and resistance R_s in series. The simulation module is as shown in Fig.14. The current and power are given by the equations (17) & (18).

$$I_p = I_{ph} - I_d \tag{17}$$

$$P_p = I_p \times V_p \tag{18}$$

From experiment, R_s is found to be = 2.13 &!. I_{ph}, being directly proportional to the radiation, is used as a measure of radiation.

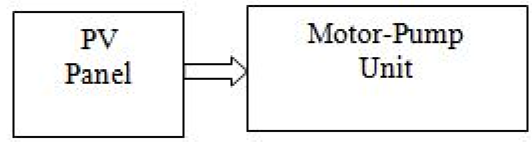

Fig.13. Solar Pumping without MPPT

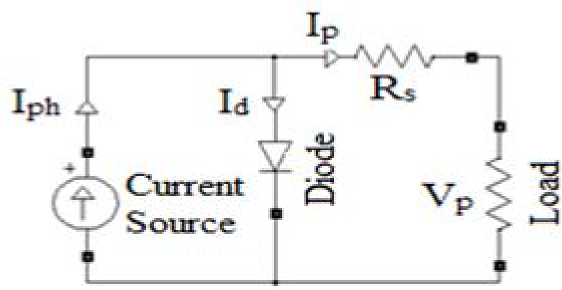

Fig.14. PV Panel Equivalent Circuit

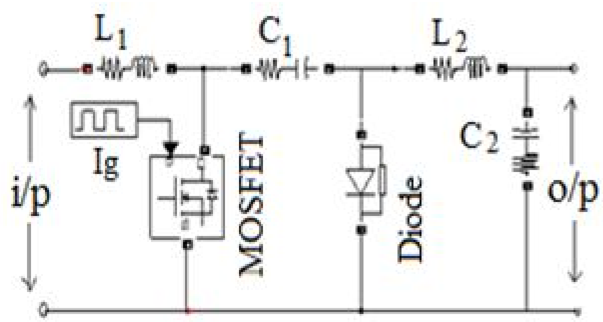

Fig.15. MPPT Converter

*MPPT Converter***:** It is the same as given in section III and designed [8] for switching frequency of 20 kHz and duty cycle range of 0.3 to 0.6. The simulation module is as shown in Fig.15.

Motor-Pump Unit: Specifications are the same as given in section III. The DC motor is modeled representing the permanent magnet as separate excitation with constant voltage source.

A. Component Simulation

As a first step, simulation of each component is done independently and verified. Simulation results are in close conformity with the experimental values for PV panel & Motor (Fig.16 & Fig.17) and with calculated values for Converter (Fig.18). This establishes validity of the simulation models of the components.

B. System Simulation

Here two cases are considered: a) Solar Pump System without MPPT b) Solar Pump System with MPPT.

Case I: System without MPPT

PV panel is connected directly to the motor-pump unit and the simulation setup is shown in Fig.19. Input required

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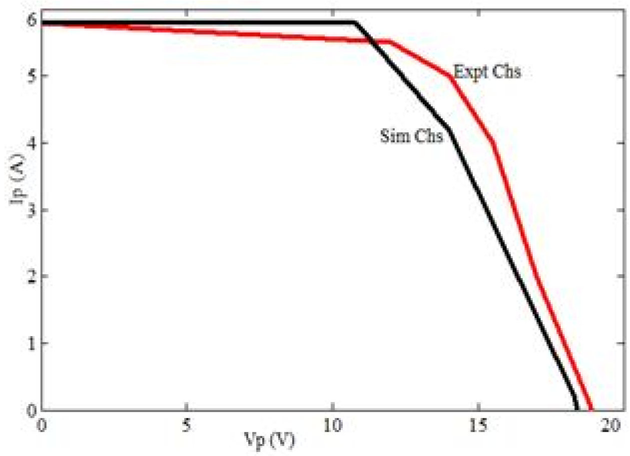

Fig.16. “V_p vs.I_p” Chs for PV panel (Experimental & Simulation)

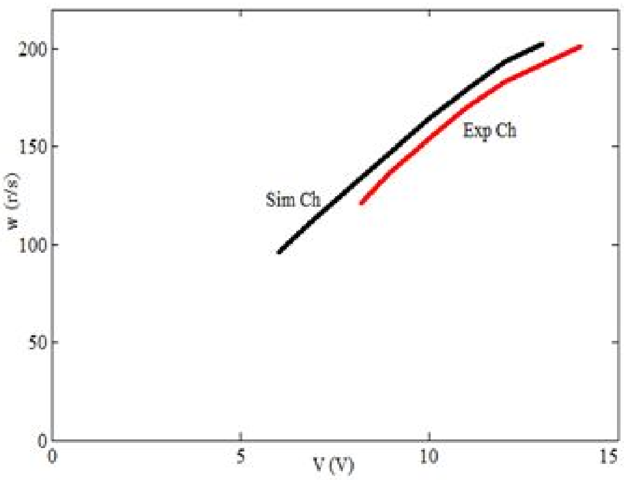

Fig.17. “Supply Voltage (V) vs. Speed (ω)” (experimental & simulation) for PMDC Motor

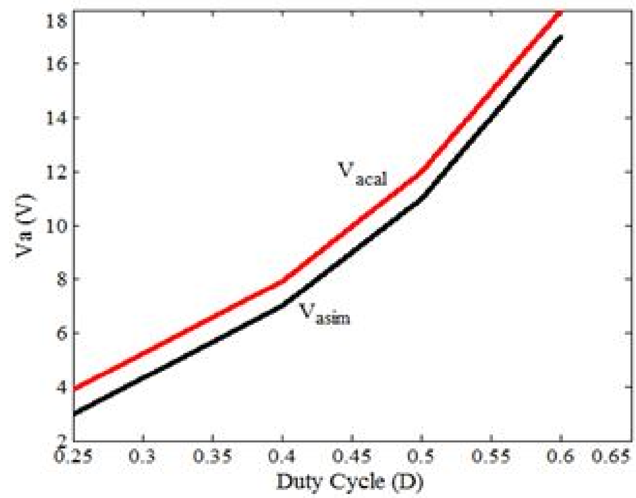

Fig.18. MPPT Converter: Calculation & Simulation results

for this block is the information of radiation and the same is given in terms of I_{ph}. The output parameters are: I_p (= I_a), V_p (=V_a), w, and T. The simulation is run for different I_{ph} and plots of maximum power and speed as a function of I_{ph} are obtained (Fig.21 & 22).

Case II: System with MPPT

The simulation setup is shown in Fig.20. Inputs required for this module are radiation level (given in terms of I_{ph}) and duty cycle D for converter. The output parameters are: I_p, V_p, I_a, V_a, w, and T. The simulation is run for different I_{ph} and at each radiation for different duty cycles D. The plot of maximum power and speed as a function of I_{ph} is obtained (Fig.21 & 22). Also, P_a and V_a are determined as a function of D at each I_{ph} (Table 2) and are plotted (Fig. 23 & Fig. 24).

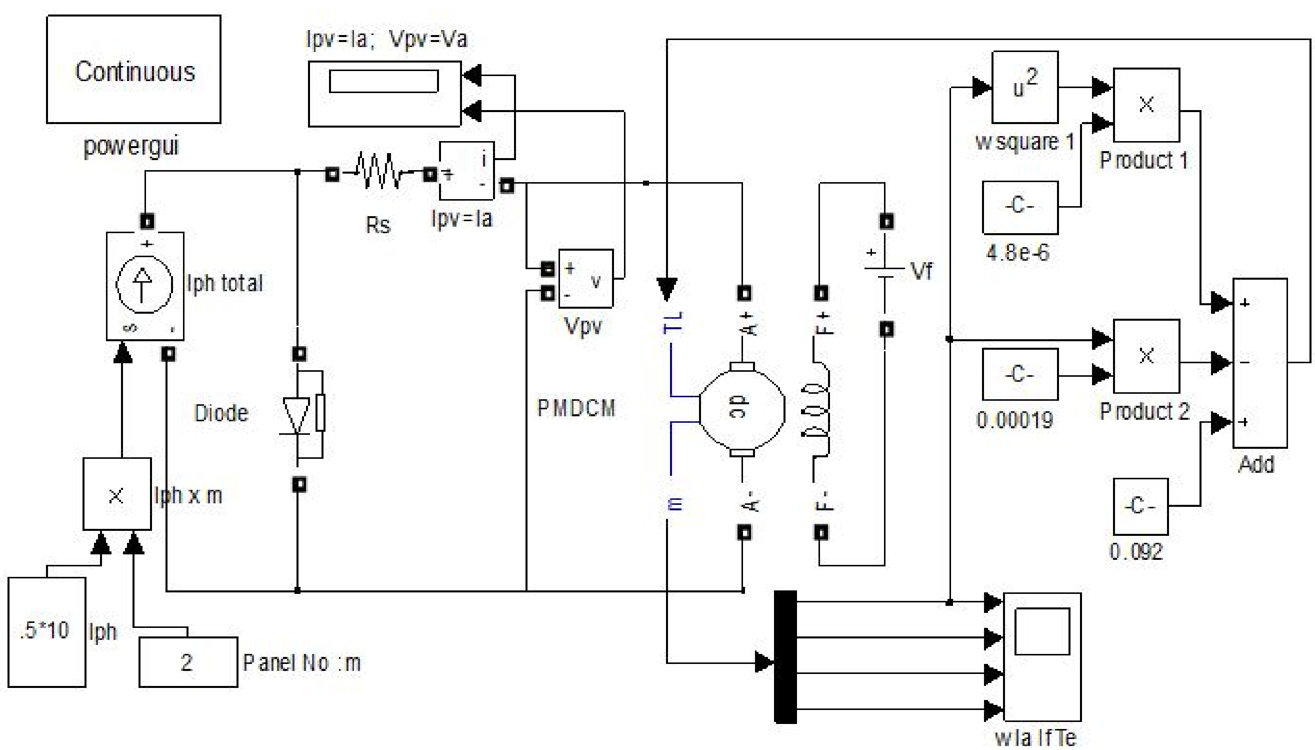

Fig.19. Simulation Model for Solar Pump System without MPPT

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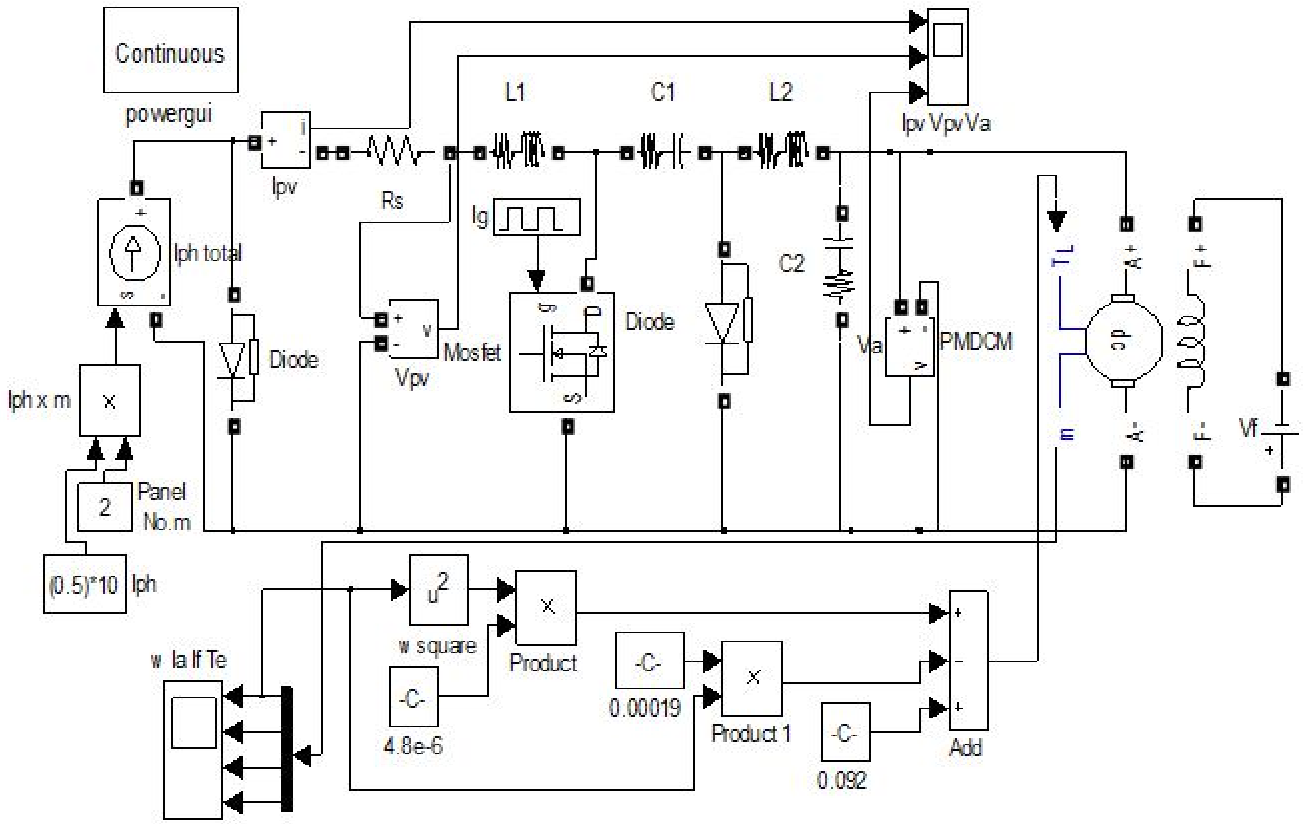

Fig.20. Simulation Model for Solar Pump System with MPPT

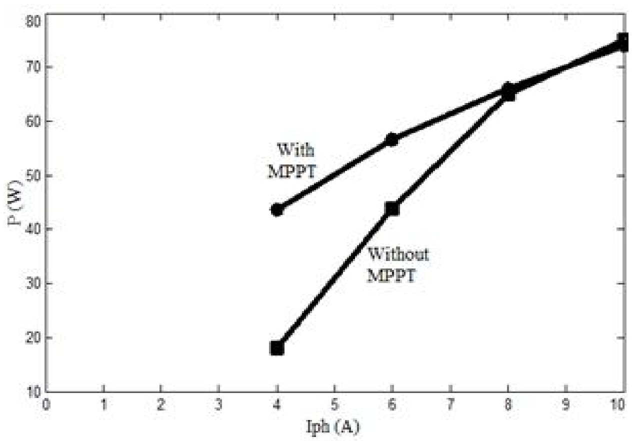

Fig.21. "I_{ph} vs. Maximum P" Simulation results

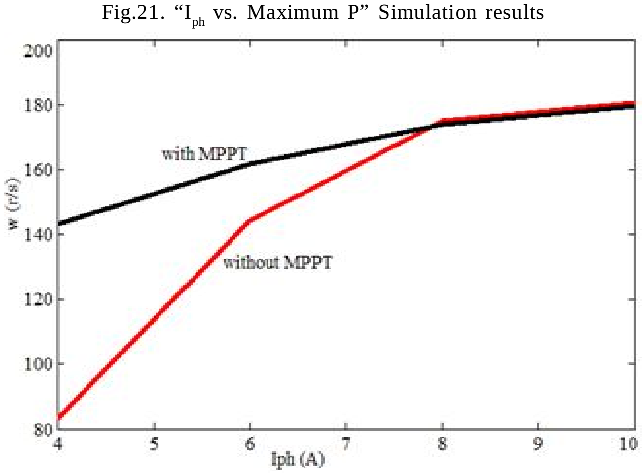

Fig.22. "I_{ph} vs. speed" Simulation results

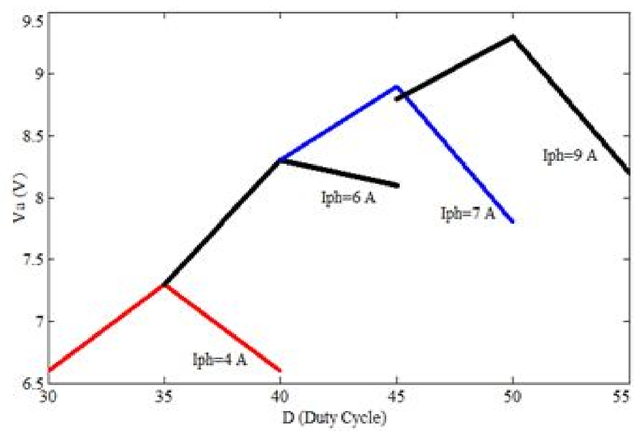

Fig.23. "Duty Cycle (%D) vs. Load Voltage (V_a)" for Motor Pump Load (Simulation results)

TABLE II. 'D, V_A, I_{PH}' SIM RESULTS FOR SYSTEM WITH CONVERTER

I_{ph} (A)	Sl. No.	1	2	3
4	%D	30	35	40
	P_a	39	**43.6**	36
	V_a	6.6	**7.3**	6.5
6	%D	35	40	45
	P_a	43.6	**56.6**	54.9
	V_a	7.3	**8.3**	8.1
7	%D	40	45	50
	P_a	56.6	**66**	50.6
	V_a	8.3	**8.85**	7.8
9	%D	45	50	55
	P_a	66	**72.5**	55.8
	V_a	8.85	**9.3**	8.2

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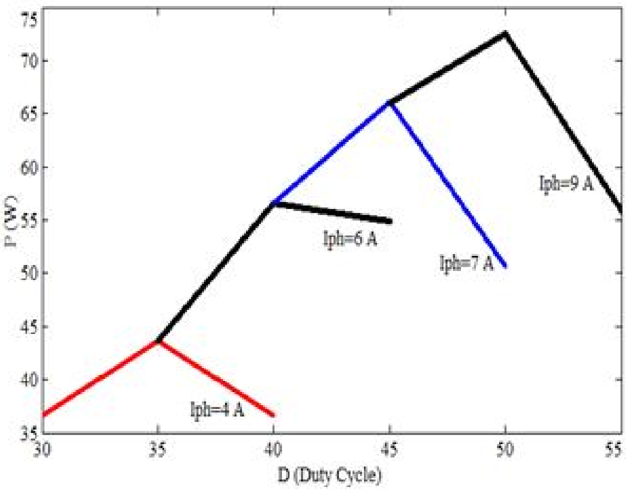

Fig.24. "Duty Cycle (%D) vs. Power (P)" for Motor Pump Load (Simulation results)

V. Critical Observations & Discussions

Following observations are made from the simulation study and results presented in section IV:

A. There is an increase in the output power P and the speed ω of the pump in the scheme with MPPT compared to the scheme without MPPT (Fig.21 & Fig.22). This feature is quite considerable at lower radiation values and decreases as radiation increases. It can be attributed to the fact that the load curve matches the panel's maximum power path more closely at higher radiation values and deviates appreciably at lower radiations. This observation reiterates the role and significance of MPPT converter in harnessing more power from the solar panel.

B. In the case of scheme with MPPT, it is also observed that at a particular radiation, the output power becomes the maximum when the motor voltage V_a becomes the maximum (Fig. 23 & Fig. 24). V_a shows typical increase/decrease trend with the corresponding variations in P_p. V_a corresponding to maximum power is an unique point. This observation from simulation work substantiates the theoretical findings presented in section III.

This means for a particular radiation, there exists a specific motor voltage at which output power becomes maximum. Hence the motor voltage V_a can be used as a control parameter for varying the duty cycle of the converter in achieving MPPT. V_a can be continuously monitored and D continuously varied so as to realize Maximum V_a which automatically ensures maximum output power at the corresponding radiation. This approach can be referred to as Maximum Load Voltage Point Tracking (MVPT). This is simpler than monitoring PV panel power which means monitoring PV Panel voltage as well as current and then multiplying them to obtain power value.

Conclusion

Water pumping is an important application of solar PV power. MPPT is opted for to harness maximum power from the PV panel so as to obtain maximum output from the pump. Widely employed approach for MPPT is to monitor the PV panel power and keep on adjusting the switching duty cycle of converter so that tapped power is always maximum.

Present paper has proposed a novel method to realise MPPT for standalone solar PV water pumping system. It is shown that the output power becomes the maximum when the motor voltage becomes the maximum. Conversely, varying the duty cycle of the converter such that load voltage is always maximum leads to harnessing maximum power output. This approach can be referred to as Maximum Load Voltage Point Tracking (MVPT). Only load voltage needs to be monitored. It is simpler than monitoring PV panel power as in that case it's necessary to measure both panel voltage and current and then find their product.

The proposal is substantiated by theoretical explanation considering two types of loads: pure resistance and Centrifugal Pump driven by brushed PMDC Motor. The Matlab-Simulink based simulation is also carried out for pump load system. Simulation results are found to be in close conformity with the theoretical findings.

Acknowledgment

The authors thank their college authorities, NITK Surathkal & SDMCET Dharwad, for the support extended in carrying out this work.

Appendix A Symbols & Abbreviations

Symbol/ Abbreviation	Significance	Unit
D	Switching Duty Cycle of Converter	
E_b	Motor Back EMF	V
Exp.	Experimental	
I_a	Load Current	A
I_a'	Value of Ia Referred To Panel Side	A
I_d	Diode Current	A
I_m	Panel Current for Maximum Rated Power	A
I_p	Solar Panel Side Current	A
I_{ph} or I_{sc}	Panel Short Circuit Current	A
K_b	Voltage constant	V/r/s
MPPT	Maximum Power Point Tracking	
MVPT	Maximum Voltage Point Tracking	
P_a	Load Side Power	W
P_m	Panel Side Maximum Rated Power	W
P_p	Panel Side Power	W
R	Resistive Load	Ω
R'	R Referred To Panel Side	Ω
R_a	Motor Armature Resistance	Ω
R_s	Equivalent Series Resistance of Panel	Ω
Sim.	Simulation	
T	Motor Torque	Nm
V_a	Load Voltage	V
V_a'	Va Referred To Panel Side	V
V_{oc}	Solar Panel Open Circuit Voltage	V
V_m	Panel Voltage for Maximum Rated Power	V
V_p	Panel Side Voltage	V
ω	Motor/Pump Speed	r/s
y	Transformation Ratio of Converter	

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